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30. Images are presented above 10 GeV where the imaging performance is highest (16).

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#### Supporting Online Material

[www.sciencemag.org/cgi/content/full/334/6059/1103/DC1](http://www.sciencemag.org/cgi/content/full/334/6059/1103/DC1)  
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# Fermi Detection of a Luminous $\gamma$ -Ray Pulsar in a Globular Cluster

The Fermi LAT Collaboration\*†

We report on the Fermi Large Area Telescope's detection of  $\gamma$ -ray (>100 mega-electron volts) pulsations from pulsar J1823–3021A in the globular cluster NGC 6624 with high significance ( $\sim 7\sigma$ ). Its  $\gamma$ -ray luminosity,  $L_\gamma = (8.4 \pm 1.6) \times 10^{34}$  ergs per second, is the highest observed for any millisecond pulsar (MSP) to date, and it accounts for most of the cluster emission. The nondetection of the cluster in the off-pulse phase implies that it contains <32  $\gamma$ -ray MSPs, not  $\sim 100$  as previously estimated. The  $\gamma$ -ray luminosity indicates that the unusually large rate of change of its period is caused by its intrinsic spin-down. This implies that J1823–3021A has the largest magnetic field and is the youngest MSP ever detected and that such anomalous objects might be forming at rates comparable to those of the more normal MSPs.

Since its launch in 2008, the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope (1) has detected whole populations of objects previously unseen in the  $\gamma$ -ray band. These include globular clusters (GCs), which are ancient spherical groups of  $\sim 10^5$  stars held together by their mutual gravity. As a class, their  $\gamma$ -ray spectra show evidence for an exponential cut-off at high energies (2, 3), a characteristic signature of magnetospheric pulsar emission. This is not surprising because radio surveys have shown that GCs contain large numbers of pulsars (4), neutron stars that emit radio and in some cases x-ray and  $\gamma$ -ray pulsations.

The first GC detected at  $\gamma$ -ray energies was 47 Tucanae (5), soon followed by Terzan 5 (6) and nine others (2, 3). Even so, no individual pulsars in these clusters were firmly identified in  $\gamma$ -rays (7). GCs are more distant than most  $\gamma$ -ray pulsars observed in the Galactic disk (8); thus, most pulsars in them should be too faint to be detected individually. The Fermi LAT lacks the spatial resolution required to resolve the pulsars in GCs,

which tend to congregate within the inner arc-minute of the cluster. Hence,  $\gamma$ -ray photons emitted by all pulsars in a given GC increase the photon background in the folded  $\gamma$ -ray profiles of each individual pulsar in that cluster.

One of the GCs detected at  $\gamma$ -ray energies is NGC 6624 (3), located at a distance  $d = 8.4 \pm 0.6$  kpc from Earth (9). With a radio flux density at 400 MHz of  $S_{400} = 16$  mJy, J1823–3021A is the brightest of the six pulsars known in the cluster. It has been regularly timed with the Jodrell Bank and Parkes radio telescopes since discovery and with the Nançay radio telescope since the launch of the Fermi satellite. The resulting radio ephemeris (table S1) describes the measured pulse times of arrival very well for the whole length of the Fermi mission, the root mean square of the timing residuals being 0.1% of the pulsar rotational period.

Thus, we can confidently use it to assign a pulsar spin phase  $\phi$  to every  $\gamma$ -ray (>0.1 GeV) photon arriving at the Fermi LAT from the direction (within  $0.8^\circ$ ) of the pulsar. We selected photons that occurred between 4 August 2008 and 4 October 2010 that pass the "Pass 6 diffuse"  $\gamma$ -ray selection cuts (1). The resulting pulsed  $\gamma$ -ray signal (above 0.1 GeV) (Fig. 1) is very robust, with an H-test value of 64 (10), corresponding to 6.8  $\sigma$  significance. The data are well

modeled by a power law with spectral index  $1.4 \pm 0.3$  and an exponential cut-off at an energy of  $1.3 \pm 0.6$  GeV, typical of the values found for other  $\gamma$ -ray pulsars [see supporting online material (SOM)]. The two peaks are aligned, within uncertainties, with the two main radio components at spin phases  $\phi_1 = 0.01 \pm 0.01$  and  $\phi_2 = 0.64 \pm 0.01$  (Fig. 1).

The pulsed flux above 0.1 GeV, averaged over time, is  $F_\gamma = (1.1 \pm 0.1 \pm 0.2) \times 10^{-11}$  erg cm $^{-2}$  s $^{-1}$ , where the first errors are statistical and the second are systematic (SOM). The large distance of NGC 6624 implies that J1823–3021A is one of the most distant  $\gamma$ -ray pulsars detected (8). This makes it the most luminous  $\gamma$ -ray MSP to date (11): Its total emitted power is  $L_\gamma = 4\pi d^2 f_\Omega F_\gamma = (8.4 \pm 1.6 \pm 1.5) \times 10^{34} (f_\Omega/0.9)$  erg s $^{-1}$ . We obtained the statistical uncertainty by adding the uncertainties of  $d$  and  $F_\gamma$  in quadrature. The term  $f_\Omega$  is the power per unit surface across the whole sky divided by power per unit surface received at Earth's location; detailed modeling of the  $\gamma$  and radio light curves provides a best fit centered at 0.9, but with a possible range from 0.3 to 1.8 (SOM).

The LAT image of the region around NGC 6624 during the on-pulse interval ( $0.60 < \phi < 0.67$  and  $0.90 < \phi < 1.07$ ) shows a bright and isolated  $\gamma$ -ray source that is consistent with the location of J1823–3021A (Fig. 2); in the off-pulse region ( $0.07 < \phi < 0.60$  and  $0.67 < \phi < 0.90$ ), no point sources in the energy band 0.1 to 100 GeV are detectable. Assuming a typical pulsar spectrum with a spectral index of 1.5 and a cut-off energy of 3 GeV, we derived, after scaling to the full pulse phase, a 95% confidence level upper limit on the point source energy flux of  $5.5 \times 10^{-12}$  erg cm $^{-2}$  s $^{-1}$ . Thus, J1823–3021A dominates the total  $\gamma$ -ray emission of the cluster. The combined emission of all other MSPs in the cluster, plus any off-pulse emission from J1823–3021A, is not detectable with present sensitivity. No other pulsars are detected in a pulsation search either.

Under the assumption that the  $\gamma$ -ray emission originates from NGC 6624, (3) estimated the total number of MSPs to be  $N_{\text{MSP}} = 103_{-46}^{+104}$ .

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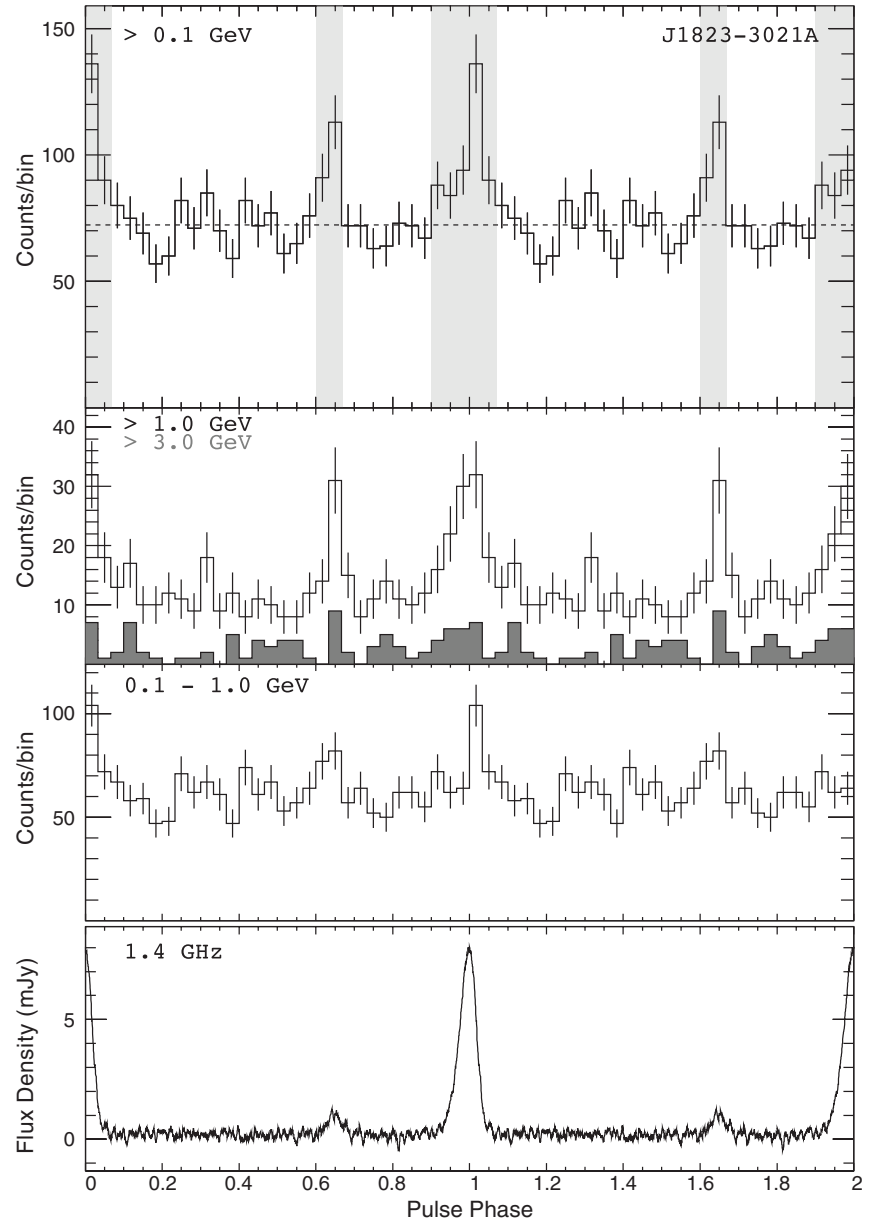
Assuming an average  $\gamma$ -ray luminosity for each MSP (2, 5), similar to the approximation made by (3), our off-pulse flux upper limit implies that  $N_{\text{MSP}} < 32$ . This is consistent with the estimate  $N_{\text{MSP}} = 30 \pm 15$  derived from the correlation between  $\gamma$ -ray luminosity and encounter rate (2). Clearly, the MSP number estimate of (3) is skewed by the presence of a single bright pulsar contributing disproportionately to its emission (12). The off-pulse emission limits can also be used to constrain alternative models for the  $\gamma$ -ray emission from globular clusters, like those invoking inverse Compton (IC) radiation (13, 14).

The spin period of J1823–3021A, 5.44 ms, is typical of MSPs. However, its rate of change  $\dot{P}_{\text{obs}} = +3.38 \times 10^{-18} \text{ s s}^{-1}$  is one to two orders of magnitude larger than for other MSPs, with the exception of J1824–2452A, a pulsar in the GC M28 (15) that has a similarly large  $\dot{P}_{\text{obs}}$  (16). A possible explanation is that  $\dot{P}_{\text{obs}}$  is mostly due to the changing Doppler shift caused by the pulsar’s acceleration in the gravitational field of the cluster along the line of sight (*a*).

$$\left(\frac{\dot{P}_{\text{obs}}}{P}\right) = \left(\frac{\dot{P}}{P}\right) + \frac{a_l}{c} \quad (1)$$

If the globular cluster has a reliable mass model, we could use it to estimate lower and upper limits for  $a_l$  and estimate upper and lower limits for  $\dot{P}$  (17). For NGC 6624, the collapsed nature of its core precludes the derivation of a reliable mass model. Furthermore, radio timing (table S1) shows that J1823–3021A is only  $0.4'' \pm 0.1''$  (a projected distance of  $0.018 \pm 0.004 \text{ pc}$ ) from the center of the cluster (18), where the values of  $a_l$  can be largest. For this reason, it has been suggested (19) that J1823–3021A is a “normal” MSP (i.e., with small  $\dot{P}$ ), its large  $\dot{P}_{\text{obs}}$  being due to its acceleration in the cluster. This conclusion was apparently strengthened by the detection of a second derivative of the spin period  $\ddot{P}_{\text{obs}} = -1.7 \times 10^{-29} \text{ s}^{-1}$  (20). This could originate in a time variation of  $a_l$  resulting from interaction with a nearby object (21). If sustained, it would reverse the sign of  $\dot{P}_{\text{obs}}$  in  $\sim 6000$  years, suggesting again that the large  $\dot{P}_{\text{obs}}$  is due not only to dynamical effects but that it is possibly a transient feature.

However, the total observed  $\gamma$ -ray emission  $L_\gamma$  must represent a fraction  $\eta < 1$  of the available rotational energy loss,  $\dot{E} = 4\pi^2 I \dot{P} / P^3$ , where  $I$  is the pulsar’s moment of inertia. Although  $I$  depends on the unknown mass of the pulsar and the unknown equation of state for dense matter, the standard assumption  $I = 10^{45} \text{ g cm}^2$  is a reasonable value for a  $1.4 M_\odot$  (mass of the Sun) neutron star. This implies  $\dot{P} > 3.4 \times 10^{-19} (f_\Omega/0.9) (I/10^{45} \text{ g cm}^2)^{-1} \text{ s s}^{-1}$ . Thus, even an unrealistic  $\gamma$ -ray efficiency  $\eta = 1$  would imply that  $\dot{P}$  is already  $\sim 10\%$  of  $\dot{P}_{\text{obs}}$ . If we assume instead  $\dot{P} \cong \dot{P}_{\text{obs}}$ , then  $\dot{E} = 8.3 \times 10^{35} \text{ erg s}^{-1}$  and  $\eta = 0.1 \times (f_\Omega/0.9)(I/10^{45} \text{ g cm}^2)^{-1}$ . Comparison with the observed  $\gamma$ -ray efficiencies of other MSPs (8, 11) shows this to be a more reasonable range of values;  $\eta \sim 0.1$  also represents the upper limit de-

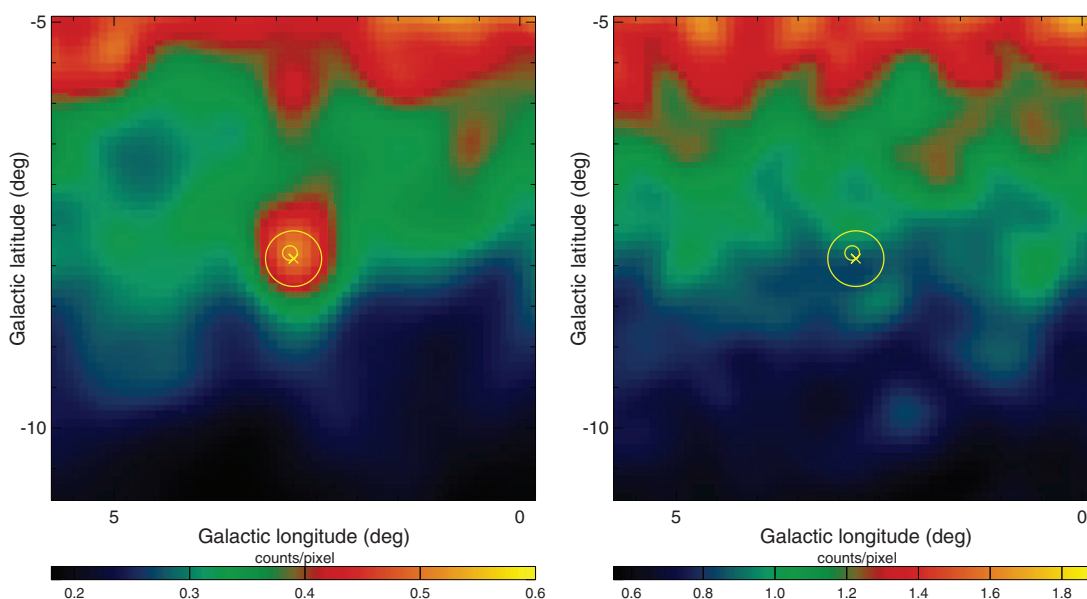


**Fig. 1.** Phase-aligned radio and  $\gamma$ -ray profiles for J1823–3021A. (**Bottom**) Nançay 1.4 GHz radio profile. (**Top and middle**)  $\gamma$ -ray profiles obtained with the Fermi LAT in different energy bands. The dark histogram is for events with  $E > 3.0 \text{ GeV}$ . The  $\gamma$ -ray background for the 0.1 GeV light curve was estimated from a surrounding ring, and it is indicated by the dashed horizontal line in the top panel. The highlighted area there shows the on-pulse region selection.

rived for the average efficiency of MSPs in 47 Tucanae (5). Therefore, our  $\gamma$ -ray detection of J1823–3021A indicates that it is unusually energetic and that most of  $\dot{P}_{\text{obs}}$  is due to its intrinsic spin-down. The pulsar has other features that suggest it is indeed unusually energetic: Its alignment of radio and  $\gamma$ -ray profiles has previously only been observed for the Crab pulsar (22) and three fast, energetic MSPs: J1939+2134 (the first MSP to be discovered), J1959+2048 (23) and J0034–0534 (24). Like some of these energetic

pulsars and PSR J1824–2452A, J1823–3021A emits giant radio pulses (25) and has a high 400-MHz radio luminosity of  $L_{400} \cong 1.1 \text{ Jy kpc}^2$  (19), the third highest among known MSPs. However, the correlation between  $\dot{E}$  and radio luminosity is far from perfect given the uncertainties in the distance estimates, moment of inertia, beaming effects, and possibly intrinsic variations of the emission efficiencies. Finally, J1939+2134 also has a large  $\dot{P}$  (26), which is thought to be caused by timing noise (TN),

**Fig. 2.** Fermi LAT  $\gamma$ -ray count map above 100 MeV for J1823–3021A during the on-pulse (Left) and off-pulse (Right) regions, as defined in Fig. 1. The  $6^\circ$  by  $6^\circ$  region is centered on the pulsar position (cross). The map was adaptively smoothed by imposing minimum signal-to-noise ratios of 13 and 16 for the on- and off-pulse regions, respectively. The large circle indicates the tidal radius of NGC 6624. The small circle shows the 99% confidence region for the location of the  $\gamma$ -ray source.



which scales roughly with  $P^{-1.1} \dot{P}$  (27). In the case of J1823–3021A, if  $\dot{P} \cong \dot{P}_{\text{obs}}$ , then TN should be one order of magnitude larger than for J1939+2134; instead, its  $\dot{P}$  is  $\sim 1.5 \times 10^2$  larger than that of J1939+2134. This is possible given the observed scatter around the TN scaling law. Thus, TN might account for the  $\dot{P}$  of J1823–3021A, but this is far more likely if  $\dot{P} \cong \dot{P}_{\text{obs}}$ .

If  $\dot{P} \cong \dot{P}_{\text{obs}}$ , we can estimate the strength of its surface dipole magnetic field:  $B_0 = 3.2 \times 10^{19} \text{G} \sqrt{\dot{P} P / (10^{45} \text{g cm}^2 (R/10 \text{km})^{-3})} \cong 4.3 \times 10^9 \text{G}$  (28) [where  $R$  is the neutron star (NS) radius, generally assumed to be 10 km]. MSPs are thought to start as normal NSs with  $B_0 \sim 10^{11-13} \text{G}$ , which are then spun up by the accretion of matter and angular momentum from a companion star. This process is thought to decrease their magnetic field to  $B_0 \sim 10^{7-9} \text{G}$ , but the exact mechanism responsible for this is currently not well understood. Our value of  $B_0$  shows that for J1823–3021A, this decrease was not as pronounced as for other MSPs.

As accretion spins up the NS, it eventually reaches an equilibrium spin period (29) given by:

$$P_{\text{init}} = 2.4 \text{ms} \left( \frac{B_0}{10^9 \text{G}} \right)^{6/7} \left( \frac{M}{M_\odot} \right)^{-5/7} \times \left( \frac{R}{10^4 \text{m}} \right)^{18/7} \left( \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right)^{-3/7} \quad (2)$$

where  $M$  is the NS mass,  $\dot{M}$  is the accretion rate, and  $\dot{M}_{\text{Edd}}$  is the maximum possible stable accretion rate for a spherical configuration (known as the Eddington rate). Beyond this, the pressure of accretion-related radiation starts preventing further accretion. After accretion ceases, the newly formed radio MSP will have  $P_{\text{init}}$  as its initial spin period. Assuming  $\dot{M} = \dot{M}_{\text{Edd}}$ ,  $M = 1.4 M_\odot$ , and  $R = 10 \text{ km}$  (as in our estimates of  $B_0$ ), we

obtain  $P_{\text{init}} = 1.9 \text{ ms} (B_0 / 10^9 \text{G})^{6/7}$ . For the value of  $B_0$  calculated above, we get  $P_{\text{init}} = 6.6 \text{ ms}$ ; that is, even if accretion had proceeded at the Eddington rate, the pulsar would not have been spun up to its present spin frequency. This is also the case for the other such “anomalous” MSP, J1824–2452A (16); for all others, we have  $P > P_{\text{init}}$ . A possible explanation is that for these two objects,  $M$  and  $I$  do not correspond to the assumptions above. If, for example,  $\eta = 0.15$ ,  $M = 1.8 M_\odot$ , and  $I = 1.8 \times 10^{45} \text{g cm}^2$  (30), we obtain  $B_0 = 3.6 \times 10^9 \text{G}$  and  $P_{\text{init}} = 4.7 \text{ ms}$ . A second possibility, suggested by Eq. 2, is super-Eddington accretion (more precisely,  $M > 1.6 \dot{M}_{\text{Edd}}$ ); this can happen for nonspherical mass accretion. A third possibility is that the value of  $B_0$  was smaller during accretion (resulting in a smaller  $P_{\text{init}}$ ), and that  $B_0$  has increased since then. This has been observed for some normal pulsars (31); however, there is no evidence of such behavior for any other MSPs.

In any case, the conclusion that  $\dot{P} \cong \dot{P}_{\text{obs}}$  implies a characteristic age  $\tau_c = P / (2\dot{P}) = 25$  million years. This is likely an overestimate of the true age of the pulsar, particularly given that  $P_{\text{init}}$  is likely to be similar to  $P$ . Thus, J1823–3021A is likely to be the youngest MSP ever detected; only J1824–2452A might have a comparable age. Because of their large  $\dot{P}$ s, both objects will be observable as MSPs for a time that is  $\sim 10^2$  shorter than the  $\sim 100$  “normal” radio-bright MSPs known in GCs. Statistically, this suggests that, at least in GCs, anomalous high  $B$ -field MSPs like J1823–3021A and J1824–2452A are forming at rates comparable to those of the more “normal,” radio-bright MSPs.

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### Supporting Online Material

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## A Homonuclear Molecule with a Permanent Electric Dipole Moment

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Permanent electric dipole moments in molecules require a breaking of parity symmetry. Conventionally, this symmetry breaking relies on the presence of heteronuclear constituents. We report the observation of a permanent electric dipole moment in a homonuclear molecule in which the binding is based on asymmetric electronic excitation between the atoms. These exotic molecules consist of a ground-state rubidium (Rb) atom bound inside a second Rb atom electronically excited to a high-lying Rydberg state. Detailed calculations predict appreciable dipole moments on the order of 1 Debye, in excellent agreement with the observations.

An electric dipole moment forms in classical systems as the result of a separation between opposite charges. A permanent

dipole moment of a quantum object requires both the charge separation and degenerate opposite-parity eigenstates. If parity and time reversal